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Piezo-driven thermoacoustic refrigerators with dynamic magnifiers

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ABSTRACT

Thermoacoustic refrigeration is an emerging cooling technology which does not rely for in its operation on the use of any moving parts or harmful refrigerants. This technology uses acoustic waves to pump heat across a temperature gradient. The temperature gradient forms across the ends of a porous body, called the stack, enclosed in a resonator. The vast majority of thermoacoustic refrigerators to date have used electromagnetic loudspeakers to generate the acoustic input. In this paper, the design, construction, operation, and modeling of a piezo-driven thermoacoustic refrigerator are detailed. The performance of the refrigerator is significantly enhanced by coupling the acoustic driver with an elastic structure, referred to as a dynamic magnifier. Proper selection of the magnifier parameters can increase the magnitude of the pressure oscillations across the stack, and consequently the temperature difference. The magnified refrigerator demonstrates the effectiveness of piezoelectric actuation in moving 0.3 W of heat across a 10 °C temperature difference with an input power of 7 W. All the theoretical predictions are validated against data from experimental prototypes. The developed theoretical and experimental tools can serve as invaluable means for the design and testing of piezo-driven thermoacoustic refrigerator configurations.

1. Introduction

Considerable attention has been devoted to the development of different types of thermoacoustics refrigerators. The first thermoacoustic device fabricated to do useful work was a thermoacoustic engine built at the Los Alamos National Lab (*LANL*) by a team lead by Wheatley [1]. However, the first known thermoacoustic refrigerator was built by Hofler [2] who was a member of Wheatley's group in the building of the first thermoacoustic engine. Soon afterward, a thermoacoustic refrigerator known as the "beer cooler" was also built at *LANL* [3]. This refrigerator used a heat driven prime mover instead of a speaker to drive it. At the Naval Postgraduate School, an extension of Hofler's refrigerator design was built to be launched on the Space Shuttle Discovery. This refrigerator is known as the Space Thermoacoustic Refrigerator (*STAR*) [4]. A thermoacoustically driven thermoacoustic refrigerator (*TADTAR*) was also built at the Naval Postgraduate School by Adeff and Hofler [5]. This refrigerator used a lens to focus light from the sun to create heat for running a thermoacoustic engine. The output from this engine was used, in turn, to drive the thermoacoustic refrigerator, completely eliminating all moving parts. With 100 W of input energy from the sun, 2.5 W of cooling power was obtained. The Shipboard Electronics Thermoacoustic Chiller (*SETAC*) was built to cool electronics aboard the U.S.S. DEYO [6]. *SETAC* was able to operate at a maximum efficiency of a COP of 21% relative to Carnot. However, when operated at the power necessary to cool the racks of electronics it was designed for, SETAC was only able to obtain a *COP* of 8% relative to Carnot. *TRITON* is one of the biggest thermoacoustic refrigerators ever built. It is named because it was designed to have the cooling power of a three ton air conditioner. Though *TRITON* is not well documented, information about it can be found on Penn State's website [7]. Tijani et al. [8] performed a number of studies on the effects of varying individual components of thermoacoustic refrigerators. He built a refrigerator based on the results of his research with a *COP* of 11% when helium was used as the working fluid. A qualitative thermoacoustic refrigerator designed to be a demo was built by Russel and Weibull [9]. This refrigerator is low cost and easy to make. However, it was very inefficient because it was designed to be a qualitative example and not to obtain quantitative results.

Ben and Jerry's ice cream funded a project at Penn State to make a clean thermoacoustic refrigerator that would cool their ice cream freezers. This refrigerator has a cooling capacity of 119 W and an

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overall *COP* of 19% of Carnot's. Prototypes of this refrigerator are currently being used by Ben and Jerry's in the Boston and Washington, D.C. areas, and if the prototypes are successful this may become the first commercially produced line of thermoacoustic refrigerators as Ben and Jerry's would like to switch all their stores over to the clean technology.

Contrary to thermoacoustic engines, thermoacoustic refrigerators use the "reverse thermoacoustic effect" where a driving acoustic wave is used as an input to induce a temperature gradient between the two ends of a porous body enclosed in a resonator, referred to as the stack.

Nearly all of the thermoacoustic refrigerators in existence are driven by electromagnetic loud speakers. However, the performance of electromagnetic loudspeakers is greatly diminished at high frequencies. For this reason, piezoelectric drivers have been used for high frequency applications of thermoacoustic refrigeration [10–12]. Piezoelectric speakers are more resistant to overloads that would normally destroy most drivers and can operate more efficiently at high frequencies. These speakers are mainly constituted of a piezo-diaphragm that exhibits mechanical strain when a voltage is applied across its electrodes, and responds by flexing in proportion to the applied electrical input. The conversion of electrical pulses into mechanical vibrations drive the acoustic pulsations along the resonator which are needed to create the temperature difference across the ends of the stack. We refer to this type of systems as Piezo-driven Thermoacoustic Refrigerators (PDTARs). Avoiding electromagnetic drivers may also be required for applications involving magnetic sensitive equipment. Unlike their electromagnetically driven counterparts, numerical and experimental models for *PDTARs* are lacking. Therefore, in this study, a *PDTAR* is designed, built, and tested. A mathematical model is developed for this system and this model is validated experimentally in order to provide a tool for designers to use with applications requiring piezoelectric actuation.

Furthermore, this paper attempts to present a novel approach to enhance the cooling effect obtained from conventional thermoacoustic refrigerators by introducing *PDTAR*s with dynamic magnifiers. Dynamic magnification refers to coupling oscillating mechanical systems with elastic structures (usually in the form of simple spring-mass systems) to amplify the vibrations. This concept has been shown in different areas to significantly increase the deflection of vibrating structures [13–15]. Dynamically magnified thermoacoustic-piezoelectric energy harvesters have been shown to be superior over conventional thermoacoustic-piezoelectric harvesters when the appropriate properties of the magnifier are chosen [16,17]. The use of dynamic magnifiers can be designed to achieve a higher efficiency and a higher power output from the piezo-element in the harvester. The current paper investigates whether the same concept can be extended to thermoacoustic refrigerators in an attempt to enhance their cooling outcome. The purpose of this work is to show the potential and feasibility of *PDTARs* augmented with dynamic magnifiers by coupling the piezo-speakers with a simple spring-mass system that can be tuned to magnify the pressure oscillations inside the resonator and as a result amplify the temperature difference across the stack ends.

The paper is organized in 6 sections. Following the brief introduction outlined in Section 1, a quick mathematical overview of the equations governing piezo-driven thermoacoustic refrigerators, taking into account the coupling between the piezoelectric speaker and the acoustic resonator, is presented in Section 2. In Section 3, the performance of the *PDTAR*s is investigated theoretically. Section 4 discusses *PDTAR*s augmented with dynamic magnifiers. The actual performance of the *PDTAR experimental prototypes* in comparison with the developed models is presented in Section 5. Finally, the conclusions are summarized in Section 6.

2. Mathematical modeling and analysis

2.1. Pressure and velocity waveforms

Based on the mathematical model suggested by [18], the variation of the spatial component of oscillating pressure $P(x)$ and velocity $u(x)$ for a one-dimensional plane wave propagation along the x-direction is governed by,

$$\frac{d^2P(x)}{dx^2} + \kappa^2 P(x) = 0 \qquad (1)$$

and,

$$u(x) = \frac{i}{\rho\omega}(1 - f_v)\frac{dP(x)}{dx} \qquad (2)$$

where κ and f_v are functions of the working gas thermo-physical properties, thermal and viscous boundary thicknesses.

The *PDTAR* presented here is modeled similar to a prototype used later for experimental validation. It consists of two adjacent tubes with two different cross sections. The piezo-speaker is hooked to the first tube, and the thus the first part of the resonator has an area equal to that of the speaker face. However, such a tube size will require a considerably large stack. Stacks of a smaller cross section have generally shown to be more effective and have a better resolution for a one-dimensional temperature gradient as heat conduction across the axis perpendicular to the wave propagation is fairly limited. For such purpose, another tube of a smaller diameter is attached to the first tube and represents the major length of the resonator. The stack is placed towards the end of the second tube. A schematic of the expected design of the *PDTAR* is shown in Fig. 1.

The *PDTAR*'s resonator, as shown in Fig. 1, consists mainly of 4 segments: the larger area tube from $x = 0$ to $x = x_1$, the "cold" tube from $x = x_1$ to $x = x_2$, the stack from $x = x_2$ to $x = x_3$, and the "hot" tube $x = x_3$ to $x = L$. For this configuration, Eq. (1) can be rewritten as,

$$\frac{d^2P_j(x)}{dx^2} + \kappa_j^2 P_j(x) = 0 \qquad (3)$$

for $j = 1, 2, 3$ or 4 depending on the location along the resonator, with:

$$\kappa^2_{1,2,4} = \kappa_o^2[1 + f_{v_{1,2,4}} + (\gamma - 1)f_{k_{1,2,4}}] \qquad (4)$$

$$\kappa_3^2 = \kappa_o^2\left[\frac{1 + (\gamma - 1)f_{k_3}}{1 - f_{v_3}}\right] \qquad (5)$$

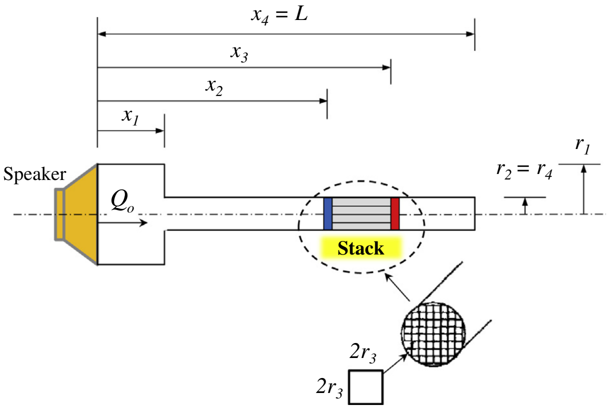

Fig. 1. Schematic drawing of a variable area *PDTAR*.